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Review on Aerodynamic Shape Optimization through Parametric Study using Computational Fluid Dynamics Analysis on the Small Wind Turbine Blade

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Abstract: The aim of this work is to find out the optimum twist angle of small wind turbine blade so as to increase its Annual Energy Production (AEP) by the means of increasing lift force on the blade of turbine in static flow condition. A horizontal-axis wind turbine (HAWT) blade is selected for optimization using an estimate code based on the Blade Element Momentum (BEM) theory. AirfoilsSG6043, BW3 and A18 are selected and utilized as candidates for designing of the micro blades. Blade element momentum theory is used to design the blade 3D geometry in the referred literature. The efficient performance of a wind turbine largely depends on the wind characteristics of the site in conjunction with the aerodynamic shape of the blades. The blade geometry will determine the torque overcome and the power generated by the rotor. By aerodynamic point of view, an economic and efficient blade design is attained by the maximization of rotor power coefficient. Some factors are different for small wind turbine blade design, than large blade. Such as, the small blades experience much lower Reynolds number flow than the large blades, hence large wind turbine airfoils may perform very poorly in small applications. The small turbines can be self-started at wind speeds which are lower, therefore the hub and tip parts are critical for the starting torque which should be able to overcome the resistance of the generator and the mechanical system. Furthermore, a well-designed wind turbine with a low cost of energy will always have an aerodynamically efficient blade. Therefore, the blade design is an important part in the whole design procedure of a wind turbine. In the current study, the objective function is restricted to the cost from the blade which is done by selecting the micro wind turbine profile, performing CFD analysis on the profile with different twist angles and analyzing the results of Lift force for the same. It is observed in CFD results of the blade that 25 degree shows most promising results in the field of lift force.
Keywords: Optimization, Blade, Aerodynamic, Lift Force, HAWT

I. INTRODUCTION

Due to the ever increasing environmental worries, oil price rising and concerns related to limited fossil-fuel resources, electricity is now being generated from renewable sources. Wind energy which is a type of renewable energy source is popular all over world for generating electricity. The power generation efficiency of wind turbine depends on the Aerodynamic shape of the blade of turbine and power performance of wind turbine rotor.

Wind turbine technology has been developed greatly over the last few decades. For optimizing the design of a wind turbine blade, the aerodynamic phenomena, such as maximum power coefficient, maximum annual energy production or minimum cost of energy are assumed to be the main objective.

The most important part in designing a wind turbine is the blade of turbine. Normally, the main aim in designing a wind turbine blade is achieving the maximum power coefficient. In the case of a micro wind energy turbine, the starting time and economic feasibility are critical in optimizing the final design of micro wind turbine blade. The starting time can be reduced by increasing the number of blades which would also increase the power coefficient, increasing the number of blades increases the overall energy of the system, which in turn increases the overall cost of the system.

A wind turbine uses rotor blades for converting kinetic energy of wind into electrical energy. Therefore, a rotor blade requires optimal aerodynamic shape to maximize its efficiency and to improve power performance. To find optimum aerodynamic design of wind blades, blade element momentum theory (BEMT) is extensively used due to its effectiveness in design and rapid calculation.

Aerodynamically, the evaluated values such as electrical power, power coefficient, axial thrust force, annual energy production (AEP) are of concern to secure design effectiveness of rotor blades.

A. Types of wind mill

1) *Horizontal Axis Wind Turbine*. Horizontal axis wind turbine also known as HAWT, has blades that look like a propeller that rotate on horizontal axis. In HAWT we have the main rotor shaft,

An electrical generator placed on the top of the tower (supporting structure). Small HAWT there is vane placed and in the large turbine there is a wind sensor coupled with servo motor to turn the turbine into the wind direction. In most of HAWT gear box is fitted to faster rotation of generator.

Fig.1. Horizontal Axis Wind Turbine (HAWT)

2) *Vertical Axis Wind Turbine:* Vertical axis wind turbine also shortened as VAWT, have main rotor shaft placed vertically. The main advantage of this is it need not point in the direction of the wind. In VAWT the generator and primary component are placed on the ground.

Fig.2. Vertical Axis Wind Turbine (VAWT)

II. LITERATURE REVIEW

“A Design Optimization Procedure for Efficient Turbine Airfoil Design”. The authors have presented optimization procedure for efficient design of turbine blade airfoil section. By considering two leading edge shapes, circular and elliptic they perform shape sensitivity study of the airfoils; nonlinear constrained optimization problem is formulated and is solved using the method of feasible directions. The aerodynamic analysis is done using a two dimensional panel code. Two point exponential approximation technique was used. From the developed procedure they successfully eliminate the sharp leading edge velocity spikes, characteristic of typical blade sections, without compromising blade performance. They conclude that circular leading edge airfoils appear to be more effective in eliminating the spikes than elliptic leading edge airfoils. However, the elliptic leading edge sections are more slender than the circular leading edge sections. Also found that two-point approximation used along with the optimizer reduces CPU time significantly and is sufficiently accurate. [1]

"Shape Optimization of Low Speed Wind Turbine Blades using Flexible Multi-body Approach". In this work flexible multi-body approach was use to extend the conventional method of dynamic modelling of small size wind turbine. Based on the floating frame of reference formulation systematic approach is developed that includes the dynamics of the flexible blade as well as aerodynamic loads. They introduce trade off procedure to optimize the airfoil geometric shape of small size wind turbines for performance and energy conversion. For low tip speed ratio (TSR), it is concluded that the adaptation of inversely tapered blades can improve the aero dynamical efficiency of such turbines. They examined inverse geometry of Betz optimized blade is and compared with straight and tapered blades. This proposed shape exhibits very good aero dynamical characteristics over the range of $TSR \leq 3$. [2]

"Aerodynamic shape optimization of wind turbine blade using parallel genetic algorithm" In this work based on genetic algorithm and blade element momentum theory aerodynamic shape optimization methodology was develop for rotor blade of horizontal turbine. The optimization study was performed at constant rotor speed, wind speed and rotor diameter for maximization of power generation. The sectional chord length, sectional twist and blade profile at root, mid and tip are defined as design parameters. The blade sections define by the NACA four digit airfoil series. They developed BEM tool, which provide power production of wind turbine. They consider 43 design parameters, Micro-GA technique with population 10 is used and optimization study is performed with wind speed 10m/s. The study achieved 10% increase in power production. [3] "A Direct Approach of Design Optimization for Small Horizontal Axis Wind Turbine Blades" This study focused on direct method for small wind turbine blade design and optimization. The authors havebuilta unique model which is mathematical and aerodynamic to obtain the optimal chord length of blade and twist angle distributions along the blade span. The airfoil profile analysis was integrated in this approach. In design optimization- Reynolds number effects, tip and hub effects, and drag effects were all considered. The optimal chord lengths of blade profile and twist angles were given with series of points and three-dimensional blade models. This approach integrates blade design and airfoil analysis process, which provides optimal parametric blade design directly with series of splines or points or 3D solid models and enables seamless link with computational fluid dynamics analysis and CNC manufacturing. [4] "Automatic identification of wind turbine models using evolutionary multi objective optimization". In this work recently developed symbolic regression method is used to identify models of a modern horizontal-axis wind turbine in symbolic form. A multi objective optimization method is used to produce dynamic models from operational data while making minimal assumptions about the physical properties of the system. They compare the models produced by this method with others, according to their estimation capacity they evaluate the trade-off between model intelligibility and accuracy. Different models are found that predict wind turbine pattern as well as or better than more complex alternatives derived by other methods. They interpret the new models to show that they often contain intelligible estimates of real process physics. [5] "Aerodynamic shape optimization and analysis of small wind turbine blades employing the old approach for post-stall region". The main objective of this study is to optimize the variation of chord and twist angle of small wind turbine blade in order to maximize its Annual Energy Production (AEP). Horizontal-axis wind turbine (HAWT) blade was analyzed and optimized using a calculation code based on the Blade Element Momentum (BEM) theory. A difficult task in the implementation of the BEM theory is the correct representation of the lift and drag coefficients at post-stall regime. In this work, the authors have used the method related to the Viterna equations to extrapolate airfoil data into the post-stall regime and the results were compared with various mathematical models. Results showed this method was accurate in predicting performance of wind turbines. Wind turbine blade efficiency calculation designed with the proposed model shows that the optimum design parameters gave rise to an increase of 8.51% in the AEP rate as compared with the corresponding manufactured operating parameters. [6] In the paper "Design of 10 kW Horizontal-Axis Wind Turbine (HAWT) Blade and Aerodynamic Investigation Using Numerical Simulation", the authors designed a horizontal-axis wind turbine (HAWT) blade with power output of 10kW has been designed by the BEM theory and the modified stall model, and the aerodynamics of the blade are also simulated to investigate its flow structures and aerodynamic characteristics. The design parameters of the blade show equal distribution of pitch angle in every section. Rated wind speed, design tip speed ratio and design angle of attack that have been set to 10 m/s, 6 and 6°, respectively. The modelling of the blade geometry done by using S822 airfoils profile and the aspect ratio of blade is 8.02 divided into radius of 3 m and chord length of 0.374 m. For predicting the performance of the designed turbine blade the improved BEM theory including Viterna-Corrigan stall model, tip-loss factor and stall delay model has been developed. Finally, the aerodynamic characteristics investigations for the turbine blade were performed by the numerical simulation. With the help of a commercial Computational Fluid Dynamic (CFD) code Reynolds averaged Navier-Stokes (RANS) equations combined with the Spalart-

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Allmaras turbulence model that describes the three dimensional steady state flow on the wind turbine blade were solved. CFD analysis results are compared with the theoretical calculations at given wind speed and it is said that this is a good approach for aerodynamic investigation of a HAWT blade. [7] A research was submitted on “Innovative approach to computer-aided design of horizontal axis wind turbine blades”. In this work the wind blade is divided into structural and aerodynamic surfaces with a G1 continuity imposed on their connecting region. Skinning is used in the current work for surface approximation. In addition, a novel approach is developed based on the redistribution of input airfoil points to ensure the compatibility of section curves. In order to evaluate errors in deviation, the Hausdorff metric is used. The fairness of surfaces is scrutinized using the standard strain energy method. To enhance further optimization algorithms are successfully integrated into a MATLAB program. The surfaces created by this method during the study were exported for analysis using the IGES standard file format and directly interpreted by commercial CAD and FE software. The application of suggested skinning method is not restricted to designing wind turbine blades; it is also applicable in ship propeller design which has warped 3D sectional airfoils. [8] A research is submitted on “Optimum Blade Profiles for a Variable-Speed Wind Turbine in Low Wind Area”. In this work 300kW variable speed horizontal axis wind turbine is designed using Blade-Element Momentum (BEM) based software. For maximum energy output chord lengths, blade twist angles and rotational speeds were allowed to change independently. Computational Fluid Dynamic (CFD) was use to validated the BEM calculation. The wind speed considered in the work is 10m/s for low wind-speed location. In analtsis, the optimized design of wind turbine achieves 50.5% efficiency at the design tip speed ratio of 7.5. The turbine can maintainan efficiency level of 50.5% over wind speeds range of 4-9 m/s by changing the rotating speeds from 16-36RPM. The results obtained from analysis conform well with the theoretical calculation. Therefore this verifies that the optimum designed blade from the BEM was reliable. [9] “Structural design and analysis of a 10MW wind turbine blade”. In this work wind blade was developed for high wind-speed areas with capacity 10MW.A composite structure using GFRP and CFRP plies was created yielding a light-weight design with a low tip deflection. FEA analysis is done for the sustainability of blade at extreme loading conditions as per international off shore standard. The results are in accordance to the design with acceptable performance of tip deflection, strains, and critical buckling load.[10]

III. NEED OF PROJECT

As the costs from operation and maintenance often can be accounted as a small percentage of the capital cost, the reduction of the capital cost becomes an essential task for designing wind turbines. Moreover, a well-designed wind turbine with a low cost of energy always has an aerodynamically efficient blade. Therefore, the blade design plays an important role for the whole design procedure of a wind turbine. In the current study, the objective function is restricted to the cost from the blade. This economy will be achieved by optimization of twist angle of blade for micro wind turbine blades.

IV. COMPUTATIONAL FLUID DYNAMICS

CAD model was created in Solid Works by using profile data and import into the ANSYS work bench.

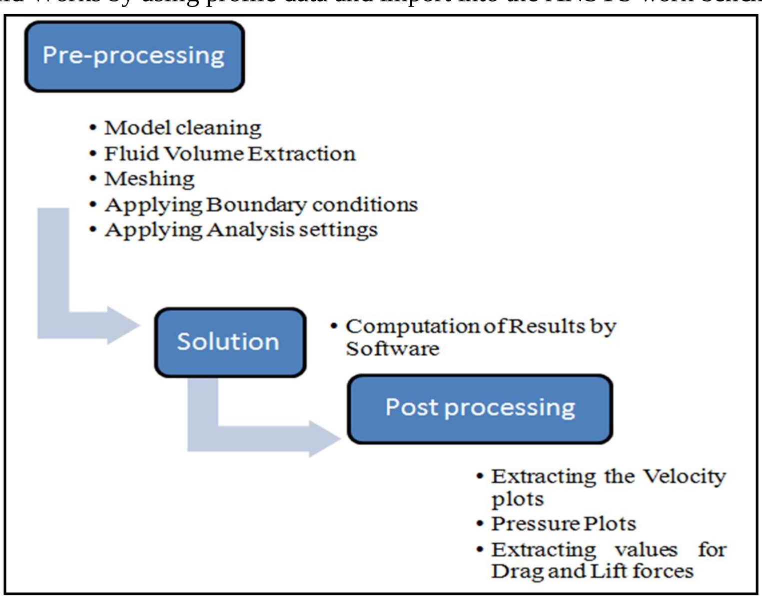

Fig.3. Flow Analysis Methodology.

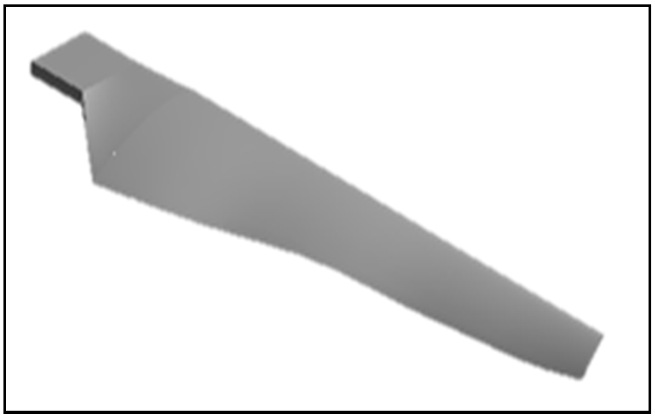

Fig.4. Wind mill Blade model.

Model cleaning is done using slice command at various cross sections to make geometry mesh able.

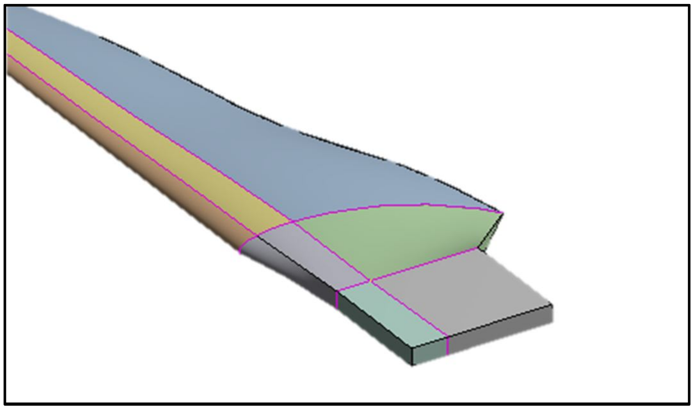

Fig.5. Model Cleaning.

For the analysis of various types of wind mill blades we create wind tunnel in ANSYS Circle of 1500 mm diameter is drawn to represent wind tunnel around the blade which extrudes 1000 mm upstream the blade and 1500 downstream the blade. Geometry is representation as fluid volume in CFD so we have to subtract solid volume from fluid so that only the zone in which fluid is present was modelled. Meshing of the wind tunnel was done using tetrahedron mesh. Around 9.14 Lakh Elements and 2.24 Lakh Nodes are used to mesh the domain,below fig gives the sectional view of meshing. Five layer boundary condition is used.

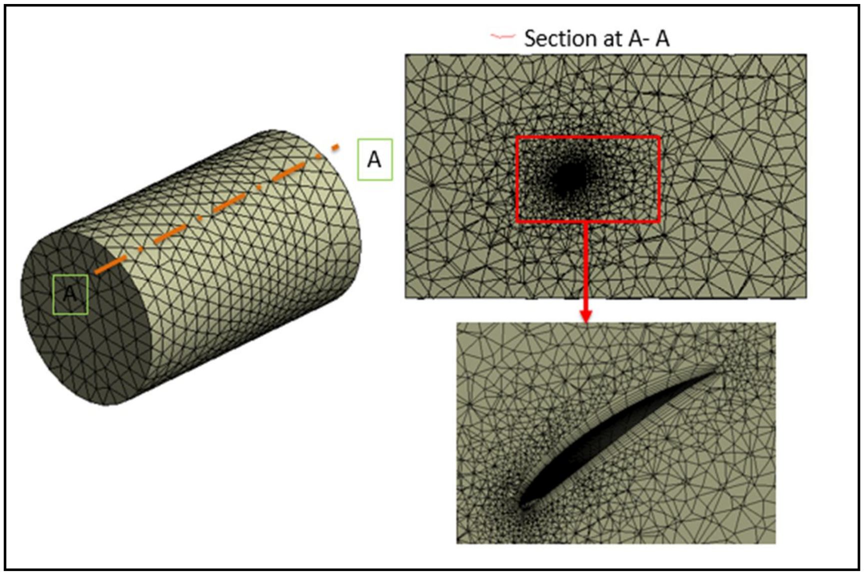

Fig.6. Meshing of fluid

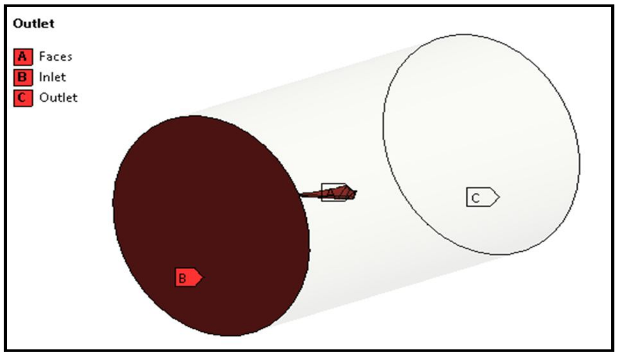

Fig.7. Boundary condition Applied

Inlet velocity of 5 m/s is applied to the side B shown in the figure in the direction aero foil shape, the opposite side is applied with the condition of atmospheric pressure. K-epsilon model is used to solve the turbulence type flow problem in Ansys fluent 16. Analysis results for the case 22 are shown below which was selected as optimum from many cases solved. Lift and Drag coefficients are plotted while solution is ran. Solution is initialized and ran for 500 cycles again and again until converged. Plots for the CFD outputs like velocity, pressure are obtained at different cross sections of the blade. Lift and drag forces on the faces component are noted down. Below fig gives the convergence plot for blade profile SG6043 with twenty two degree twist angle.Below fig gives the graph of coefficient of lift at various iterations. Lift Coefficient Cl – 0.525when solution is converged.

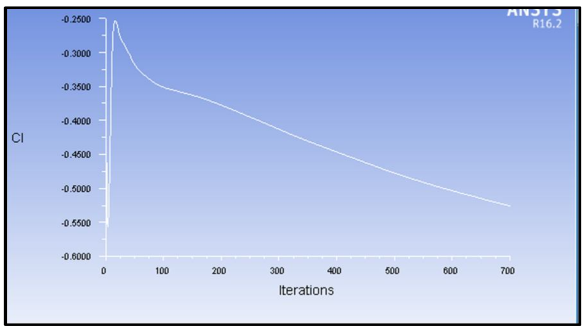

Fig.8. Graph of lift coefficient

Below fig gives the graph of coefficient of drag at various iterations. Drag Coefficient Cd – 0.199when solution is converged.

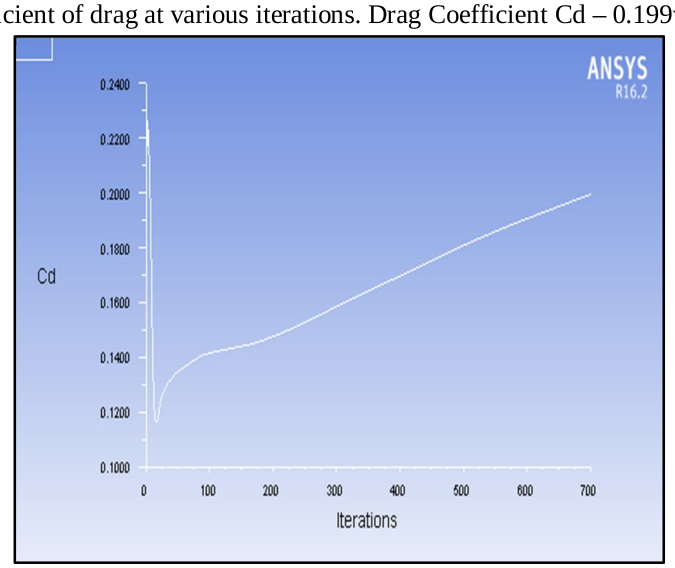

Fig.9. Graph of lift coefficient.

Optimized angle of twist velocity and pressure plots at different plane cross sections are shown below for CFD analysis of blade profile SG6043.

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Below fig shows the Blade Geometry with 24 Degree Twist.

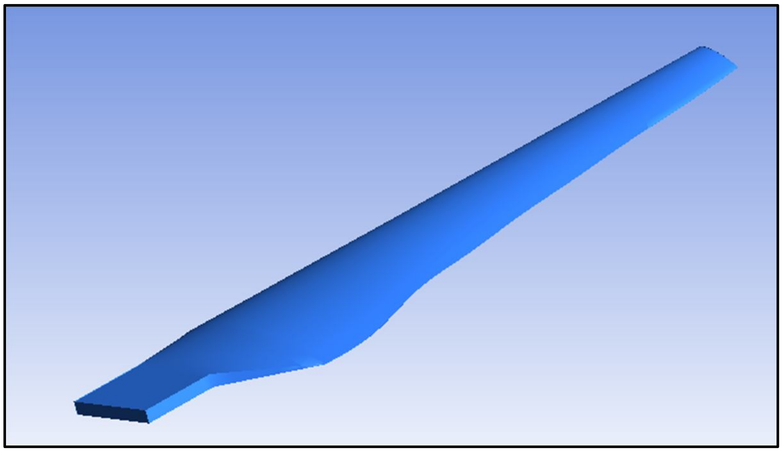

Fig.10. Blade SG6043 with 24 degree twist.

For the velocity plot at various cross section 9 slicing planes at the reporting distance of 18 mm placed.

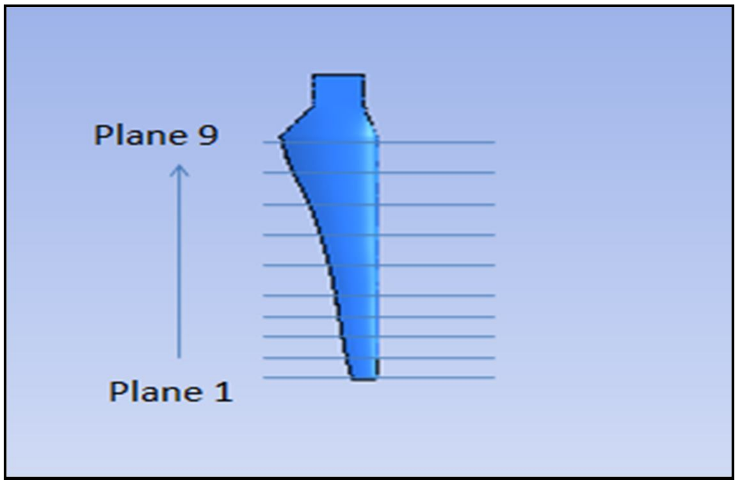

Fig.11. Schematic of 9 Slicing plane

Below fig gives us the velocity contour plot at section plane 1

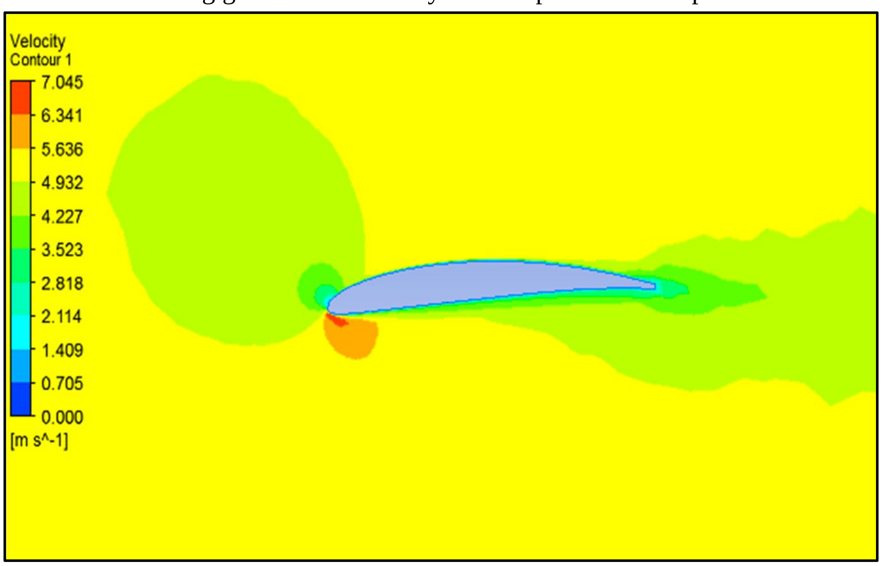

Fig.12. Velocity plot at section plane 1 for 24° twist

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Pressure plot for blade profile SG6043 with 24° twist at section plane 1.

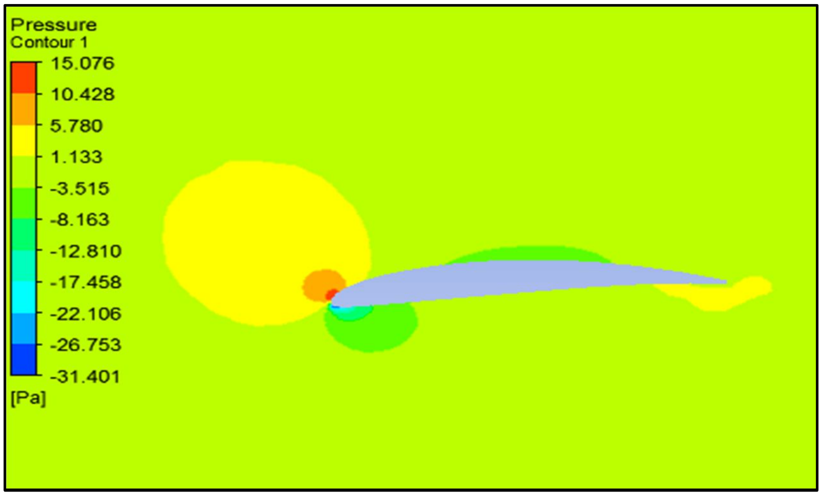

Fig.13. Pressure plot at section plane 1 for 24° twist.

Below fig gives us the velocity contour plot at section plane 5

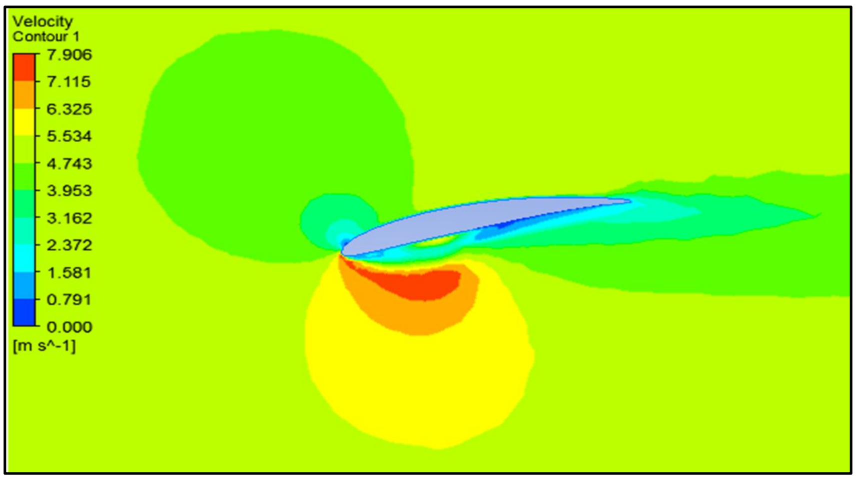

Fig.14. Velocity plot at section plane 5 for 24° twist

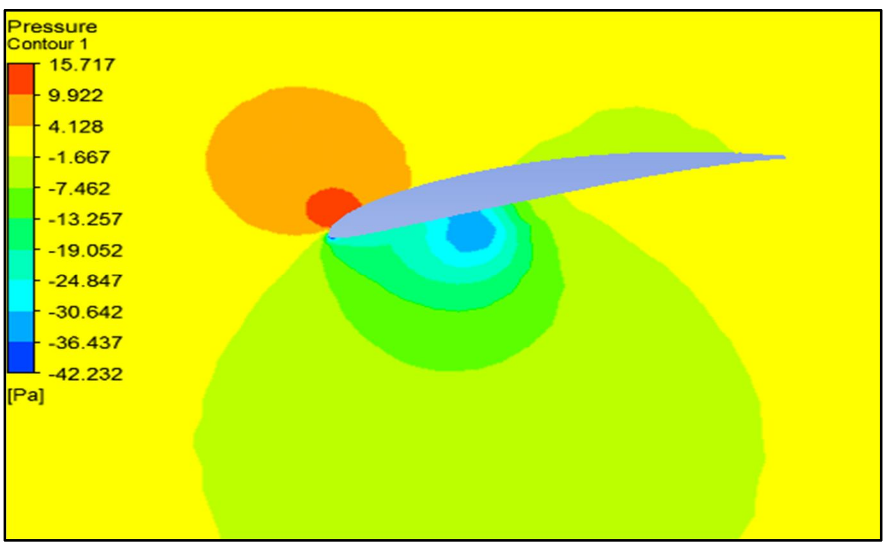

Fig.15. Pressure plot at section plane 5 for 24° twist.

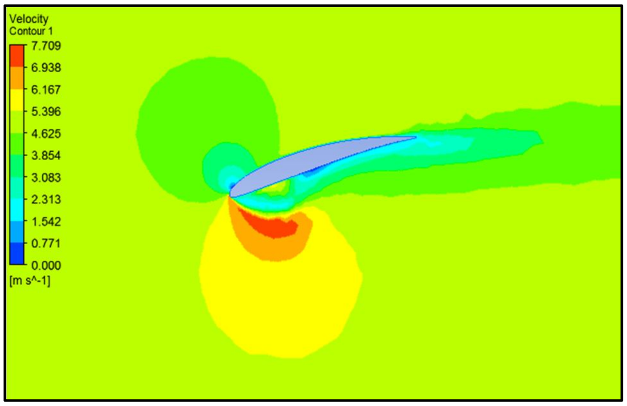

Fig.16. Velocity plot at section plane 9 for 24° twist.

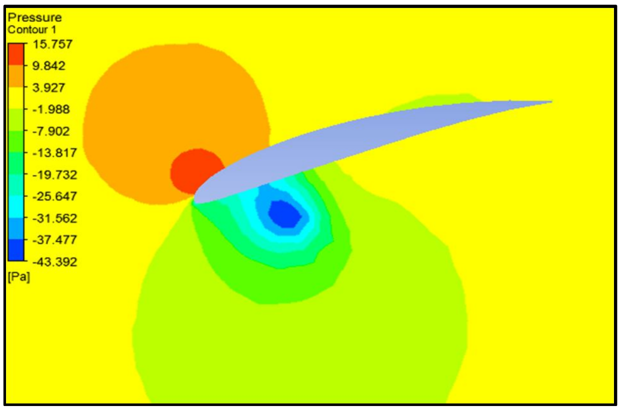

Fig.17. Pressure plot at section plane 9 for 24° twist.

In all the results plots at different cross section planes pressure and velocity hot spots above and below the shape of the profile can be observed clearly. Those hot spots are the reason for the drag and lift force exerted on the blade profile. Values of those forces are observed as below for 24 degrees twist angle iteration blade profile SG6043.

Drag Force - 0.162 N

Lift Force - 0.381 N

After the findings of the SG 6043 are studied at similar angles CFD is ran for the profiles A 18 and BW 3. Models for the same are shown in the figures below.

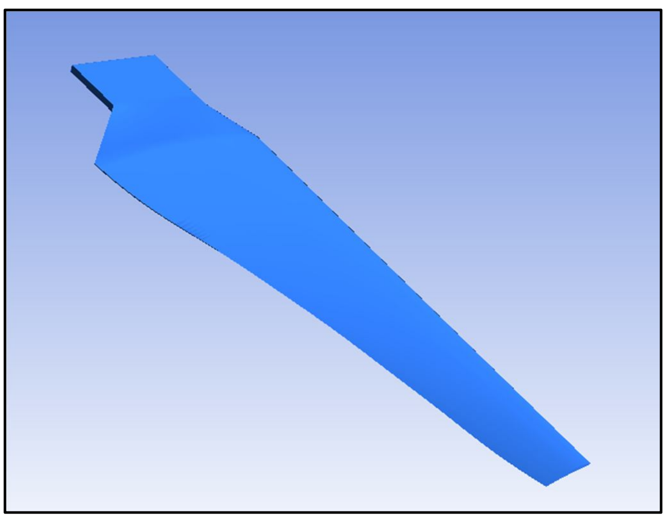

Fig.18. Optimized A18 Geometry

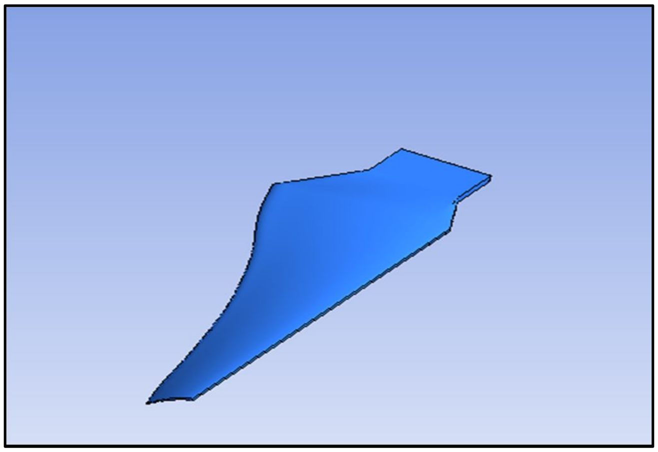

Fig.19. Optimized BW3 Geometry

V. EXPERIMENTAL TESTING

The following results were obtained from the testing of the blade inside the wind tunnel. Forces on the blade are observed by the load cell attached to the blade as in axial direction of wind flow force observed as 0.157 N (16.3 grams) and in vertical direction force observed was 0.363 N (36.5 grams). Wind velocity observed just near the wind blade section in the middle was 4.2 m/s.

Fig 20. Wind Tunnel Test Setup from Inlet Side

Fig 21: Wind Tunnel Test Setup from Outlet Side

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VI. RESULTS DISCUSSION

Table 1. Values of Drag and Lift Force (N) for blade profile SG6043

Angle of Twist (Degrees)	Cl	Cd	Fl(N)	Fd(N)
0	0.0052	0.00588	0.0053	0.0052
10	0.15	0.0758	0.09236	0.04636
18	0.22	0.14	0.13	0.0852
20	0.32	0.16	0.24	0.121
22	0.525	0.199	0.3528	0.1364
24	0.61	0.3	0.381	0.162
42	0.39	0.41	0.25	0.24
52	0.449	0.441	0.27	0.275

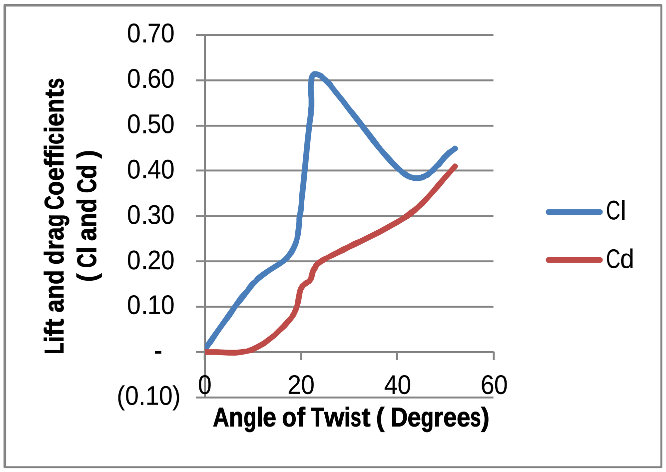

Fig.20. Graph of Cd and Cl with respect to blade twist angleSG6043

As the angle of twist increases for the profile the area that is exposed to the air attack increases also which will increase the resistance to the flow over the blade profile in the direction of flow. That is the reason Coefficient of drag constantly goes on increasing as the angle of twist increases from 0 to 52 degrees from 0.005 to 0.44 for profile SG6043. Drag forces are proportionally changing to drag coefficients. Lift on the other hand depends on the resistance to the flow in the direction perpendicular to the flow direction, which is almost negligible at 0 degrees twist but increases steeply up to 24 degrees twist from negligible to 0.61 it decreases as the twist is further increased as area resisting in the perpendicular direction reduces after that twist angle. Pressure plots show the zones created at 24 degrees which are sharpest.

Table 2. Values of Drag and Lift Force (N) for blade profile A 18

Angle of Twist (Degrees)	Cl	Cd	Fl(N)	Fd(N)
10	0.12	0.10	0.10	0.09
18	0.32	0.16	0.19	0.10
20	0.36	0.18	0.22	0.12
22	0.44	0.23	0.26	0.14
24	0.57	0.28	0.35	0.16
42	0.50	0.36	0.30	0.22
52	0.52	0.45	0.32	0.28

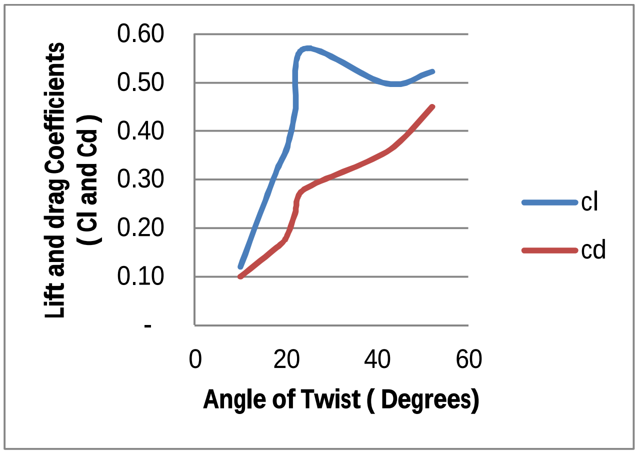

Fig.22. Graph of Cd and Cl with respect to blade twist angle A18 profile

As the angle of twist increases for the profile the area that is exposed to the air attack increases also which will increase the resistance to the flow over the blade profile in the direction of flow. That is the reason Coefficient of drag constantly goes on increasing as the angle of twist increases from 10 to 52 degrees from 0.1 to 0.45 for profile A18. Drag forces are proportionally changing to drag coefficients. Lift on the other hand depends on the resistance to the flow in the direction perpendicular to the flow direction, which is 0.12 at 10 degrees twist but increases steeply up to 24 degrees twist from negligible to 0.57 it decreases as the twist is further increased as area resisting in the perpendicular direction reduces after that twist angle. Pressure plots show the zones created at 24 degrees which are sharpest.

Table 3. Values of Drag and Lift Force (N) for blade profile BW3

Angle of Twist (Degrees)	Cl	Cd	Fl(N)	Fd(N)
10	0.10	0.07	0.08	0.04
18	0.11	0.10	0.10	0.09
20	0.27	0.12	0.15	0.10
22	0.35	0.19	0.12	0.21
24	0.54	0.24	0.36	0.25
42	0.44	0.33	0.27	0.20
52	0.48	0.42	0.31	0.26

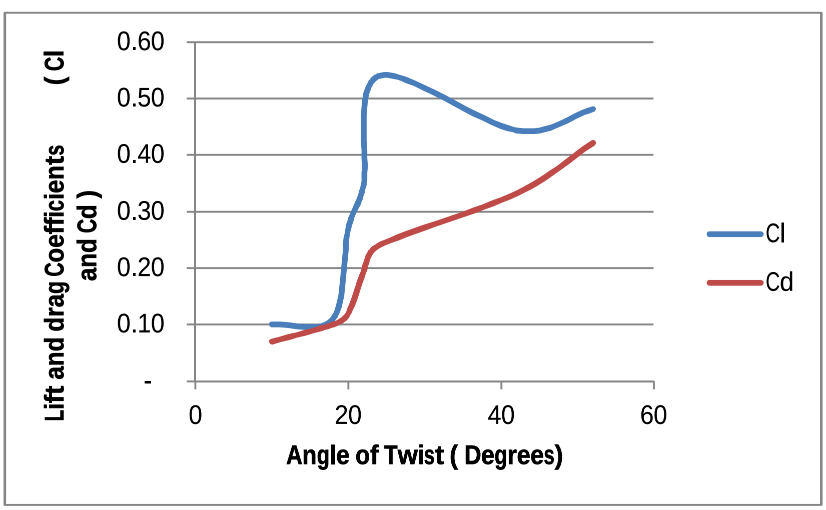

Fig.23. Graph of Cd and Cl with respect to blade twist angle BW3 profile

Cd and Cl are plotted with changes in the twist angle of the blade. Below is the graph of coefficient of lift and coefficient of drag Vs Angle of twist. From the graph it is observed that the coefficient of lift increases up-to 24 degree angle of twist then goes decreasing till 45 degree and again rises as angle twists on. Coefficient of drag goes on increasing as the angle of twist increases.

VII. CONCLUSION

As HAWT operated by the lift force it is important to have high lift force for the blade designed while drag force cannot be very high as it may cause design weight addition.

In this study we carried out the CFD analysis of SG6043 blade for the twist angle of 0°,22°,42° and 52°.It is found that the up to 25 ° angle of twist the coefficient of lift goes increasing and then goes decreasing till 45° angle of twist ,while coefficient of drag increase in liner manner till 42°. It can be clearly seen from the results that for the similar sizes of the turbine blade the angle of twist is independent of the profile and pattern in the Cl and Cd variation can be generalized for all small wind power turbines. The best performing profile at 5 m/s seconds is SG 6043 at 24 degree angle of twist. So optimum angle of twist for the blade profile SG 6043 is selected as 24 degrees from the study above as it gives us highest value of the lift force for average value of the drag on the turbine blade. That is 0.38 N lift forces while drag of 0.16 N. A18 and BW 3 also follow the similar pattern of relation between angle of twist and the lift and drag coefficients according to CFD results.

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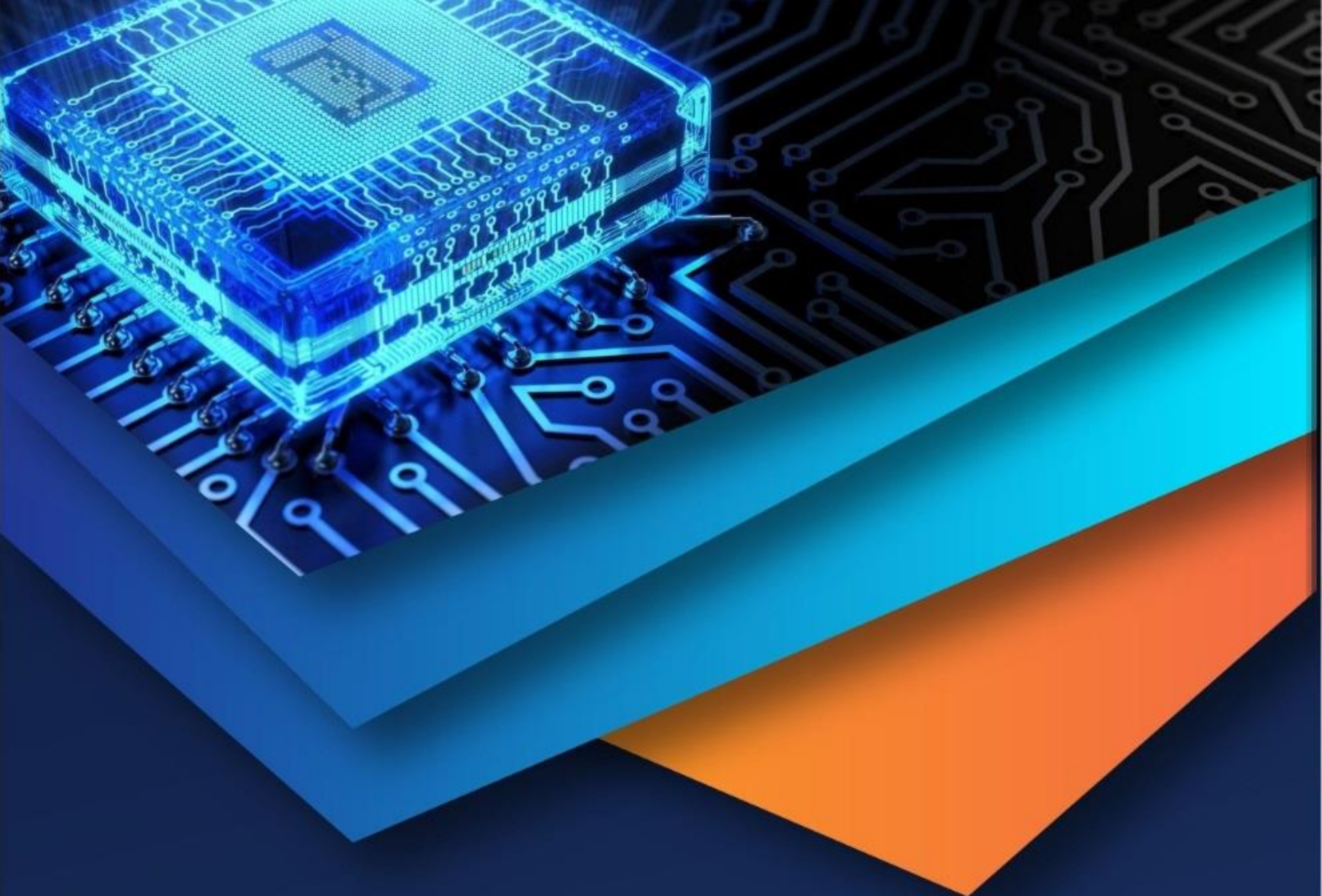

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